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Research Article

Lisbon Urban Heat Island Updated: New Highlights about the Relationships between Thermal Patterns and Wind Regimes

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Urban growth implies significant modifications in the urban climate. To understand the influence of the city of Lisbon on the urban boundary layer, a mesoscale meteorological network was installed in 2004. The main goals of the present study are to update the results of the research published in 2007 and to bring more precise information about the relationship between the Urban Heat Island (UHI) and the regional and local wind systems. The highest frequencies of the UHI were found in the city centre (Restauradores). In the green park of Monsanto, the highest frequency occurred between −2 and 0°C. During the summer, the effect of the breezes was observed in Belém, lowering the temperature. The "strong" UHI (intensity >4°C) occurred more often during the summer, with median values of 2°C by night and 1.8°C by day. The highest frequencies of UHI occurred for winds between 2 and 6 m/s and were not associated with atmospheric calm, as pointed out in the literature. Winds above 8 m/s inhibit the occurrence of strong UHI in Lisbon. Summer nighttime strong UHI should be further investigated, due to the heat stress consequences on the population and probable increase of energy consumption.

1. Introduction

Urban growth and land use changes imply considerable modifications on the atmospheric dynamics and induce local climatic changes. The consequent changes in aerodynamic roughness also induce alterations in the wind flows, which act as one of the major factors in urban climate and microclimates [1]. The authors of this study [1] found a reduction of about 30% in the mean wind speed in the Lisbon urban boundary layer, due to both topography and built-up areas, when compared with the wind speed simulations where only regional winds and the local topography were taken into account. These values may reach 40%, if the roughness length increases to 1.5 m windward of the city. This will contribute to increase the heat stress and urban atmospheric pollution, with major negative consequences on human health and quality of life for the urban population.

In recent years the problems caused by urban climate modifications led to an increasing number of studies about thermal bioclimates [2–4], also bringing about new ideas and solutions to solve them [5–8].

Amongst the climatic effects of urbanization, the urban heat island (UHI) pattern is the best documented example of involuntary human climatic modification [2, 9–11].

The urban heat island is defined by the difference of temperature between the city centre and the surrounding areas [12]. This clear and simple definition has led to the development of different methodologies to effectively calculate the UHI in different cities (the definition used in this study is presented in Section 2).

Lisbon is located on the western coast of Portugal, at the latitude of 38°43′ N and the longitude of 9°9′ W. The city is located about 30 km to the east of the Atlantic Ocean, on the right bank of the Tagus River (Figure 1). It occupies an area of 84 km^2 and has 547733 inhabitants, while the Metropolitan Area population has more than 2 M people (2011 census). The topography of the city is well differentiated: the maximum altitude is about 226 m (in the Monsanto Park, a small hill in

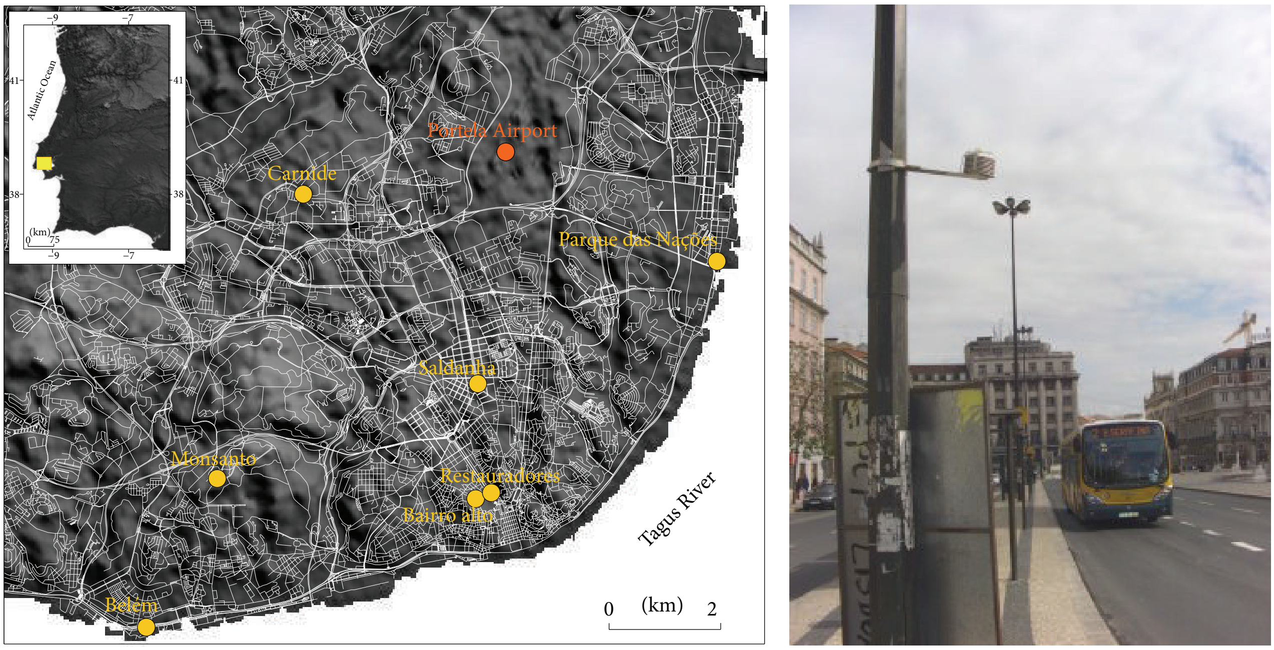

Figure 1: Location of the measurement sites of the Lisbon mesoscale network. On the right, the radiation shield, containing the thermohygrometer, in "Restauradores," is shown.

Table 1: Characterization of the measurement sites of the Lisbon mesoscale network (RES: Restauradores, BAI: Bairro Alto, SAL: Saldanha, CAR: Carnide, MON: Monsanto, BEL: Belém, and PAR: Parque das Nações).

	Measurements sites						
	RES	BAI	SAL	CAR	MON	BEL	PAR
Mean altitude* (m)	32.4	55.8	85.1	106.7	160.8	5.8	4.2
Minimum distance to the Tagus River (m)	1225	1168	3765	7810	2635	181	75
Buildings* (%)	65.7	73.6	70.8	24.7	0.6	19.8	21.6
Mean building height* (m)	11.6	11.4	16.2	15	7.5	9.9	16.5
NDVI (normalized difference vegetation index)	0.1	0.1	−0.1	−0.14	0.12	0	0.29

*Measured within a square of 500 m, centred over the observation site (based on Alves and Biudes [13]).
Source: adapted from Alcoforado et al. [14]

the western part of the city) and 160 m in the urbanized area [5].

According to Andrade [15] the urban heat island effect occurs normally in the south, with undefined boundaries. This thermal pattern is also influenced in Lisbon by a set of nonurban features, such as the relief and the proximity to the Tagus estuary and to the ocean.

In Lisbon, the wind blows predominantly from the north and northwest throughout the year. Western and southwestern as well as eastern and northeastern winds are also frequent in the cold season [16]. However, for 45% of the spring and summer days, a relatively strong north wind (the *Nortada*) dominates [17]. This natural north ventilation is very important because it promotes pollutant dispersion and reduces natural and anthropogenic heat loads. However, in the last 20/30 years Lisbon has been growing towards the north; the buildings create an enormous barrier to the north wind and environmental problems for the south of the city can occur [1].

After numerous studies based on field measurements in the 1980s and 1990s [2], a mesoscale meteorological network was set up in 2004 by the CEG/CliMA (Climate and Environmental Changes research group) of the University of Lisbon (Figure 1), in order to understand the influence of the city of Lisbon on the urban heat island effect. Based on the first temporal data series [2, 14] the researchers concluded that the heat island effect occurs more frequently during the night, especially in situations of weak and moderate wind (5 m/s). This was justified by the urban effect together with shelter from the northern winds, usually cool or cold, in summer and in winter [2, 14]. During winter and summer days, situations of heat island interchange with "cool islands"; these are due to cool air advection from the Tagus estuary, "shadow effect" from the buildings and other modifications of the energy balance (such as heat stored inside the buildings during the day) [18]. The mean intensity of the nocturnal UHI (representing the difference between the average temperature in the city centre and "rural" areas), varies from 0.5°C to 4°C,

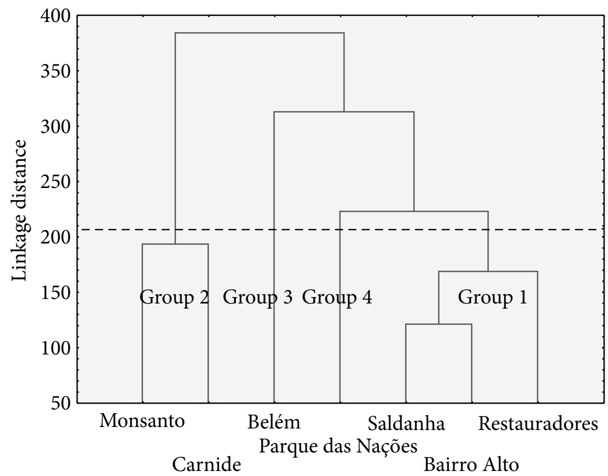

FIGURE 2: Similarity groups of the thermal deviations of each station of the urban mesoscale network and the Portela Airport. Data: CliMA-CEG and IPMA.

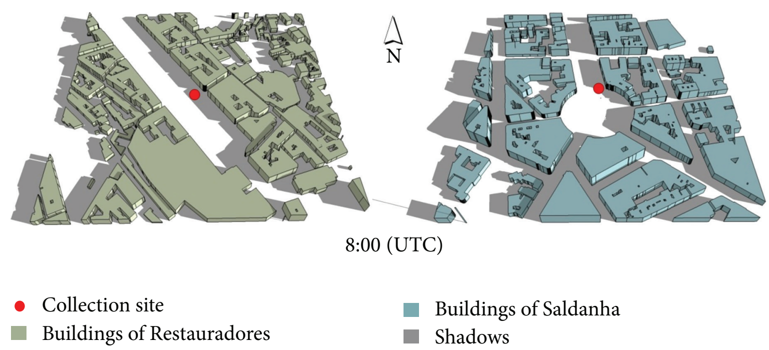

FIGURE 3: Building's shadow effect during the equinox in Restauradores and Saldanha sites.

as found by Alcoforado and Andrade [2]. In 2007, Alcoforado et al. [14], based on new data collected during a period 678 days from the Lisbon mesometeorological network, concluded that the urban heat island effect had a mean intensity of 3°C.

The main goal of the present study is to update the results with new observational data and to bring new light on the relationships between the UHI patterns and the wind conditions in Lisbon.

2. Material and Methods

The results presented here are based on data measured by a mesoscale network currently consisting of seven thermo-hygrographs. The network was first installed in the early 2000s, as a temporary network, and the first results were divulged in 2003 [15]. From 2004 onwards, a permanent mesoscale network was installed and results were presented in a paper in 2007 [14]. In the present paper 31000 hourly data were analysed, for the period 2004–2012 (with some gaps due to technical problems). The CliMA research group, of the Centre of Geographical Studies of the University of Lisbon, maintains this network. To assess data quality, the thermohygrometers are regularly (every 2 to 3 years) submitted to tests to verify for the need for calibration. No meaningful differences were reported between the devices since the beginning of the observations, and therefore we consider that data quality is insured.

In the present study several temporal scales of analysis were used as follows:

(a) hourly data, frequency of temperature deviations; urban heat island intensity;

(b) Daytime and nighttime, urban heat island intensity (see explanation bellow);

(c) Seasonal, mean hourly temperature deviations; urban heat island intensities; hourly mean wind speed and directions.

The measurement sites are open (SVF ≥ 0.69), so that the microclimatic influence of buildings or nearby trees are banned. Following the advice given by T. R. Oke, a consultant for one of our projects on urban climatology (CLIMLIS) and based on [20], this network aims to study the mesoscale features of the Lisbon thermal fields. The instruments are Gemini data loggers (model TinyTag Plus) and are located on public lighting poles, about 3.5 m above the ground [21], inside a radiation protection shield (Figure 1).

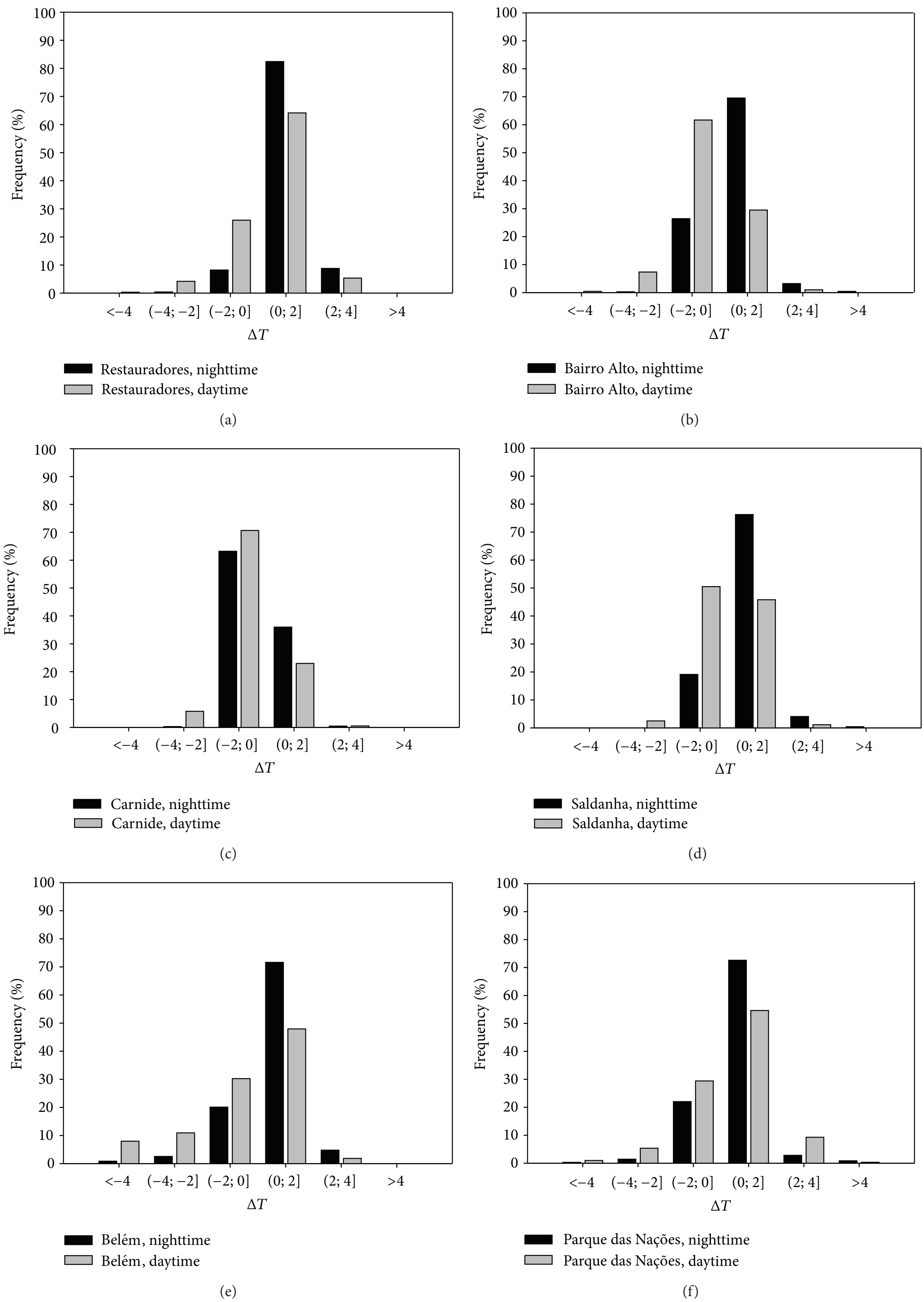

Figure 4: Continued.

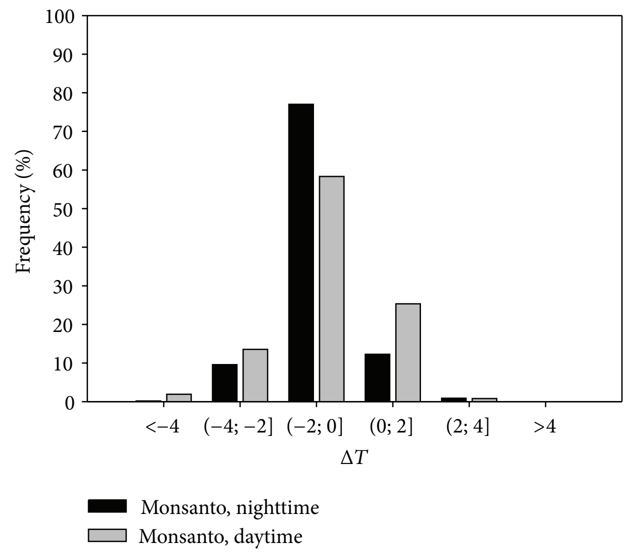

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Figure 4: Frequencies of air temperature deviations between the observation points and the Portela Airport meteorological station. *Low intensity*: urban-rural differences up to 2°C; medium intensity: from 2 to 4°C; *strong intensity*: >4°C (Classification based on García [19]).

The measurements are undertaken every 15 minutes, but the present analysis is based on hourly averages. The location and features of each measurement site are indicated in Figure 1 and Table 1.

The (ΔT) frequencies were obtained from the differences between all measuring sites and the Portela Airport meteorological station. Alcoforado and Andrade [2] (such as other authors, in several different cities [10, 22]), applied this concept in Lisbon, as described in

$$\Delta T = T_U - T_A, \quad (1)$$

where T_U corresponds to the air temperature of each measuring or collecting site in the city and T_A is the air temperature representative of a nonurban area. To follow the same methodology [2], the analysis of the thermal deviations between urban stations and a reference one was carried out. In order to do so, the meteorological data from the Portela Airport was used (orange point in Figure 1) as reference (T_A). In order to assess the thermal similarities between the city measurement sites, a tree clustering analysis with all data was carried out (Figure 2). As a result, the measurement sites were divided into 4 groups. Group 1 comprises the central city sites (Restauradores, Bairro Alto, and Saldanha), group 2 the peripheral sites (Monsanto and Carnide), and 3 and 4 are only represented by the riverside sites—Belém and Parque das Nações, respectively. These sites are representative of the oceanic influence and sea breezes (Belém) and the Tagus estuarine breezes (Parque das Nações).

It is difficult to find an universal criteria to calculate the UHI intensity (UHII) [20]. According to Andrade [15], the UHI in Lisbon was considered to occur each time the temperature in the central sites (group 1) was superior to the temperature registered in the peripheral places (group 2). The intensity of the UHI was calculated as the difference, at a specific moment, between the central and the peripheral sites following

$$\text{UHII} = T_C - T_P, \quad (2)$$

where T_C corresponds to the highest air temperature among the central sites and T_P to the lowest air temperature among the peripheral sites.

The riverside areas (Belém and Parque das Nações) were not considered in this analysis, because their thermal behaviour is specific only to them, due to the frequent Tagus and Ocean breezes [5, 14].

The UHI intensities were classified according to García [19]: *low*: urban-rural differences up to 2°C; *medium* with differences ranging from 2 to 4°C; *strong* from 4 to 6°C; and *very strong* with UHI intensities superior to 6°C.

However, particularly during the day, "negative" UHI or cool islands occur in Lisbon, as referred above.

Due to the large range of daytime UHI intensities in Lisbon [2, 15], for the analysis of the temperature variation (ΔT) and frequency of UHI intensities, the data was divided into nighttime (20:00 to 6:00 h) and daytime observations (10:00 to 18:00 h). By selecting these periods, the radiation conditions that can cause thermal anomalies due to the facets shadowing near sunrise and sunset is partially avoided. In fact, depending on the hour, the day, the season and the position of the buildings, some microclimatic differences may arise, unrelated to the mesoclimatic factors (Figure 3).

3. Results and Discussion

3.1. Temperature Differences (ΔT). The frequencies of the various ΔT classes can be observed in Figure 4. During the daytime, four sites (Carnide, 70.6%; Bairro Alto, 61.6%; Monsanto, 58.3%; and Saldanha, 50.5%) presented the highest

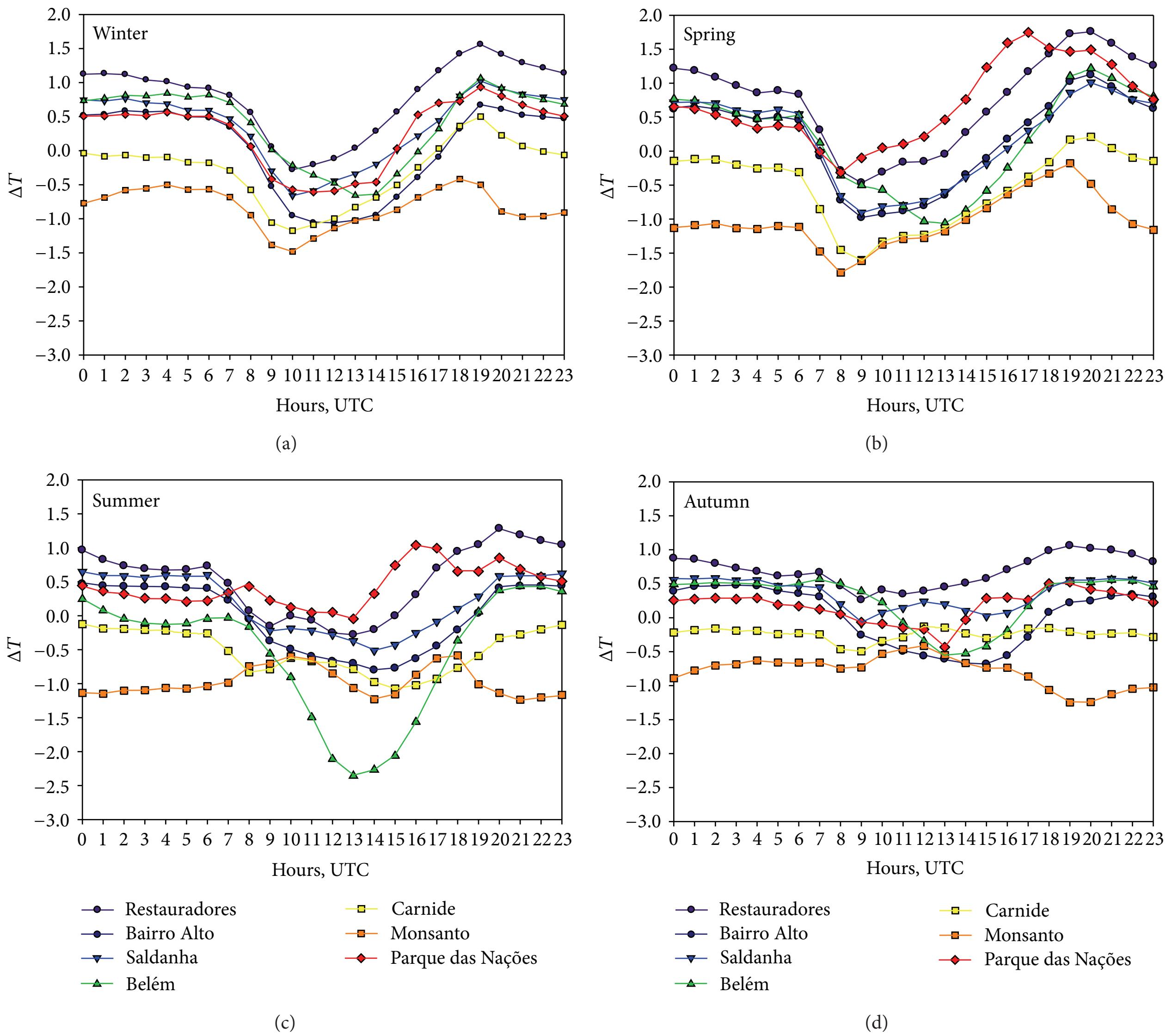

FIGURE 5: Seasonal hourly average deviations between the urban sites of the CEG/CliMA mesoscale network and Lisbon Airport. Winter: DJF; Spring: MAM; Summer: JJA; Autumn SON.

frequency of values between (-2°C < ΔT < 0°C). During the nighttime and contrasting with the previous values, the class between (0°C < ΔT < 2°C) is the most frequent in five sites (all, excluding Monsanto and Carnide). A tendency to register values of $\Delta T < 0^{\circ}$C in Carnide and Monsanto, during day and nighttime, can be clearly observed.

During the daytime, Belém (near the river) and Monsanto (a green park) were the locations where the higher negative intensities ($\Delta T \leq -4^{\circ}$C) were observed (with frequencies of 7.9% and 1.9%, resp.). In the class rage of (-4°C < ΔT < -2°C) the "air refreshment" effect can also be observed, highlighting the importance of breeze systems and green areas in the improvement of thermal conditions in the city.

Fortunately, the instances when $\Delta T > 4^{\circ}$C (for which values, serious health problems can occur [14, 23–25], especially during periods of high temperatures) were not frequent.

Figure 5 shows the seasonal mean of ΔT. Monsanto presents a lower ΔT than the other measurement sites, for nearly every season. It is worth mentioning that Monsanto is Lisbon's largest green area having, therefore, the ability to intercept solar radiation, besides cooling the surrounding air by the process of evapotranspiration [26, 27]. In summer, the southwest Tagus breeze reaches Monsanto, which also cools down the atmosphere, although it is stronger and more frequent in Belém. Also during the summer, between 10:00 h and 16:00 h, it was observed that, on average, Belém registered lower temperatures than Monsanto. According to Vasconcelos and Lopes [28] breezes in Lisbon are usually set off during the morning period (10:00 h UTC), when the temperature of the Tagus estuary is cooler than the city. As the continent keeps warming throughout the day, the *Nortada* (north wind) can increase and invalidate the estuarine breeze

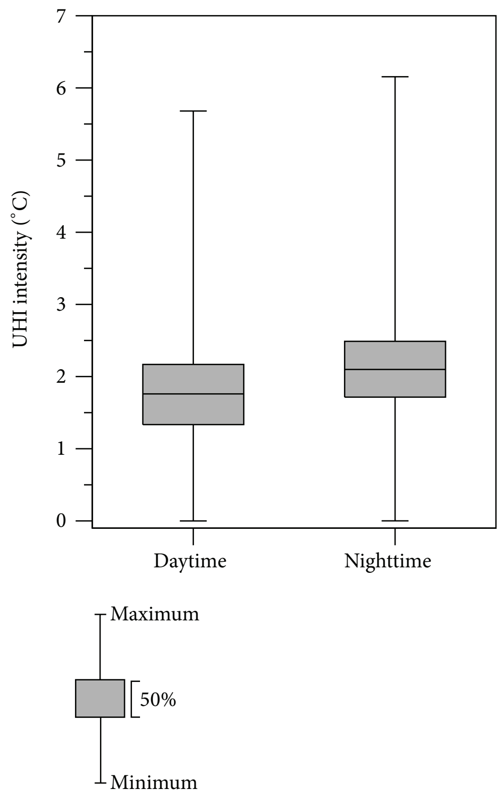

Figure 6: Nighttime and daytime urban heat island intensity (UHII).

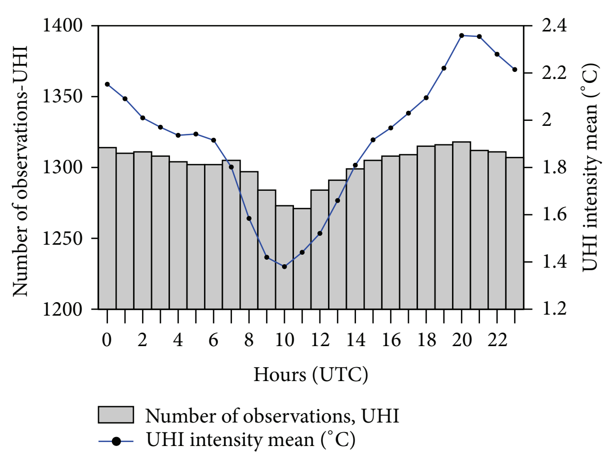

Figure 7: UHII (hourly means) in the period 2004–2012.

[17]. The flow can oppose the Tagus breeze throughout the day. The riverfront may be, on average, 3.5°C cooler than the inner city [28].

In Parque das Nações it was verified that, during the spring and summer, from 9:00 h 17:00 h, ΔT was higher than for the other measurement sites. Despite being a riverbank area that may be affected by the estuarine breezes in the morning, it is not as exposed to the ocean, unlike Belém, which is the first site the cool sea air reaches. Parque das Nações cools down by regional wind flows from northeast or when eastern and south-eastern breezes occur [17, 28].

Restauradores mostly displayed the highest values of ΔT in the mesoscale network, a fact previously observed by Alcoforado et al. [14]. Bairro Alto, and Saldanha alternate as the 2nd and 3rd sites registering highest ΔT. Carnide (urban periphery) was the second site with the lowest ΔT.

3.2. Urban Heat Island Intensity (UHII). According to the above-stated results, the presence of a heat island in Lisbon has been observed and the recent data confirmed the tendencies found in previous research [2, 14, 15] where the temperatures registered in central areas (Saldanha, Restauradores,

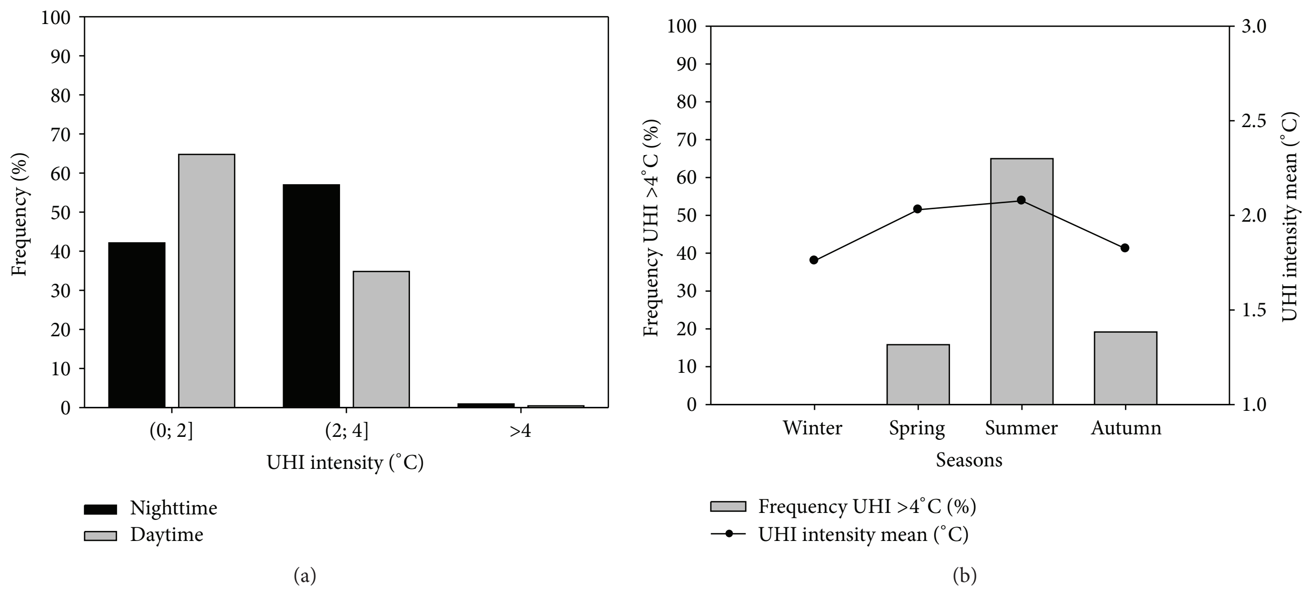

Figure 8: Frequency of the UHII during night- and daytime periods (a) and seasons (b). Winter: DJF; Spring: MAM; Summer: JJA; Autumn SON.

and Bairro Alto) were higher than the temperatures observed in the surrounding sites (Monsanto and Carnide). However, new highlights are now much clearer: Figure 6 shows that during the night 50% of the UHI varies from 1.7 to 2.4°C, whereas during the day it is between 1.3 and 2.2°C. The mean and the median of the nocturnal urban heat island are 2°C, while the diurnal only reaches 1.8°C. The maximum UHII observed was 6.1°C, during the night and 5.7°C during the day (114 cases with UHI > to 4°C were observed). We should note that these values are rare and must be better investigated in future research.

Taking into account all the observations (Figure 7), the rhythm of the average Lisbon UHI becomes clear: more intense at 20:00 h and 21:00 h (2.3°C) and less at 10:00 h (1.4°C).

Figure 8(a) shows that, during the day, the highest frequency of UHII (64.7%), occurred in the *low intensity* class (up to 2°C). During the night, the *medium intensity* class (2 to 4°C) reached the highest frequency (57%), results that confirm the eminently nighttime characteristics of the UHI in Lisbon. This had already been mentioned by [2, 14, 15]. As for the seasonality, UHI occurs in every season. However, the strong UHII > 4°C (Figure 8(b)) was observed more often during the summer (65%, mean is 2.1°C), with only 19.2% in autumn and 15.8% in spring and was never observed in winter (the lowest UHII mean temperature: 1.7°C).

3.3. Lisbon Wind Regimes. Figure 9 displays the seasonal wind regimes from 2004 to 2010. As was mentioned before, the northwestern and northeastern winds prevail in autumn and winter. In spring and summer northwestern winds predominate: the *nortada*, which is characterized by wind speeds above 5 m/s [1, 2, 17], occurs in 45% of the days. Its origin is associated with the strong atmospheric pressure gradient between the thermal low over the Iberian Peninsula and the Atlantic anticyclones [2, 5].

When the *nortada* slows down or ceases, a second (local) ventilation pattern develops in Lisbon; in 30% of summer days estuarine or ocean breezes occur [2, 5, 15, 17].

3.4. The Relationship between Urban Heat Island (UHI) Patterns and Wind. UHI is related to the wind speed, wind direction, and time (hours) [12, 29–31]. Figures 10(a), 10(b), and 10(c) illustrate these relationships. As the wind speed increases, the UHII presents a tendency to decrease (Figure 10(a)). However, unlike other cities, higher frequencies of UHII in Lisbon do not occur during situations of atmospheric calm (as noted by Alcoforado et al. [14]). In fact, the highest frequencies of UHII occur with winds of 2 to 4 m/s (32.6%) and 4 to 6 m/s (29.4%). The strong UHII (>4°C) occurs, more frequently, with winds between 2 to 4 m/s (45%) and 4 to 6 m/s (25%).

However, very strong winds prevent the development of the UHII [31]. Winds of about 6 and 7 m/s are critical values for the existence of the maximum UHII in Seoul (South Korea) and Salamanca (Spain) [32, 33]. In Lisbon, it was observed that from 8 m/s on, strong intensity urban heath islands do not occur (Figure 10(a)). Figure 10(b) demonstrates that UHI occurred with winds in every direction. However, strong UHII occurs more frequently with north and northwestern winds, followed by southwestern and western winds. The considerable number of observations of strong UHII occurred between 21:00 h and 00:00 h (Figure 10(c)).

4. Conclusions

The analysis of the Lisbon mesoscale network data, for the time series between 2004 and 2012, showed a high variability in the urban thermal field. The highest frequencies of $\Delta T > 0$°C were found in Restauradores, both during the day and at night, especially in the class between 0 and 2°C. In Monsanto, the highest frequency was found in the class

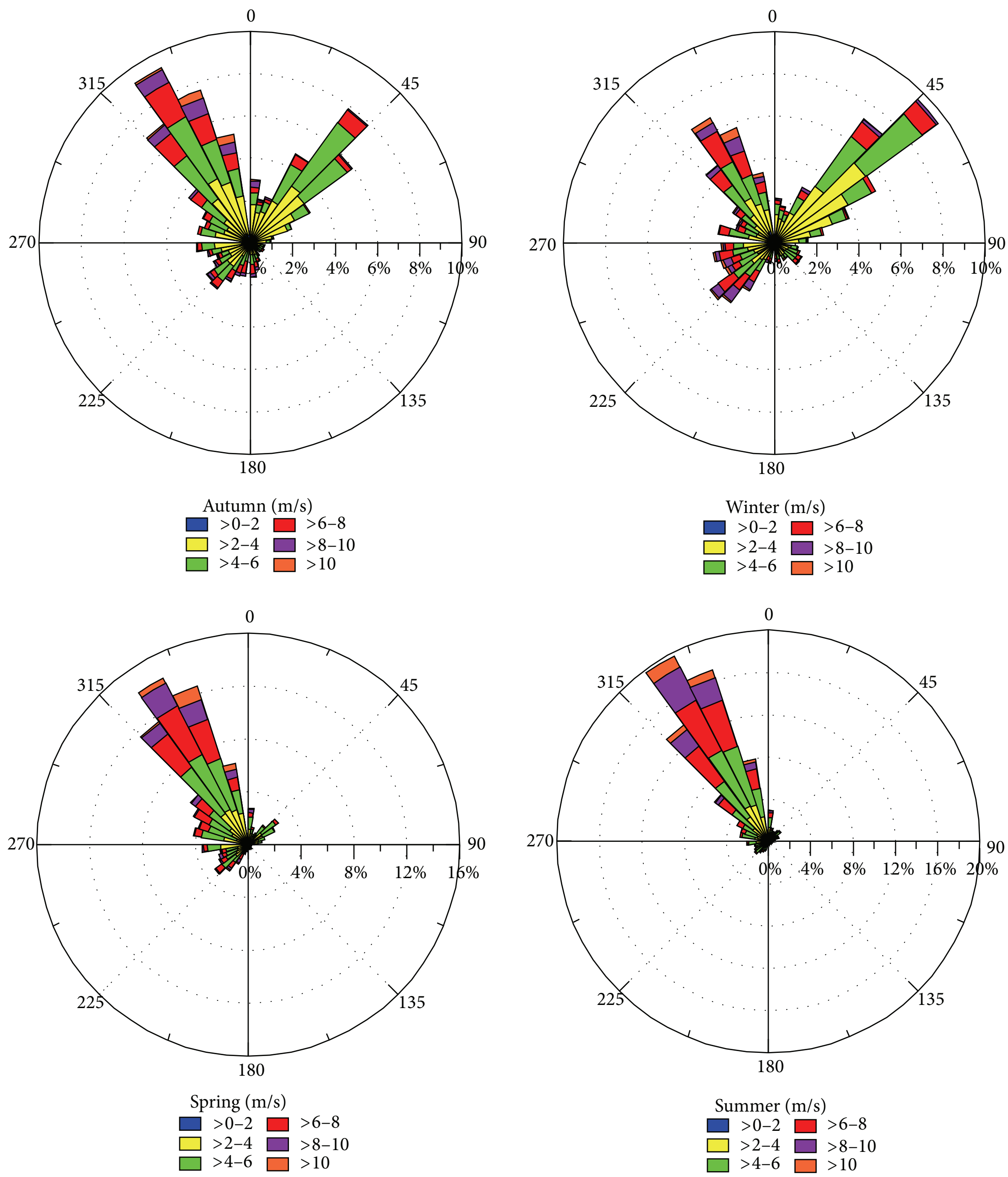

FIGURE 9: Seasonal regimes of wind speed and direction. Autumn: SON; Winter: DJF; Spring: MAM; Summer: JJA. Data: IPMA.

between −2 and 0°C. In Belém, during the summer, the effect of the breezes was observed, attenuating the air temperature and, consecutively, presenting prevalence of $\Delta T < 0$°C, as observed in the study of Vasconcelos and Lopes [28].

Urban heat islands were observed throughout the year; however, strong UHI (UHII >4°C) occurred more often during the summer, where the highest seasonal difference mean (2.1°C) was also recorded, whereas, in the winter, the lower UHI mean was verified (1.7°C).

The median value of the UHI intensity during the night and day periods were, respectively, 2°C and 1.8°C (this last value is slightly different from the one verified by Alcoforado et al. [14] during the day, 1.6°C). Although the number of extreme positive differences during the night are rare (only 114 cases with temperature > than 4°C), these cases must be investigated in future research because they probably correspond to situations of extreme heat stress, which endanger human health in the city and lead to more energy consumption (the maximum UHII observed was 6.1°C).

In Lisbon, the highest frequencies of UHII took place with winds of 2 to 4 m/s and 4 to 6 m/s, which differs from the atmospheric calm pattern defined by Oke [12], due to the importance of the shelter effect from Northern cold or cool winds. The strong UHI intensity occurred, mainly, with

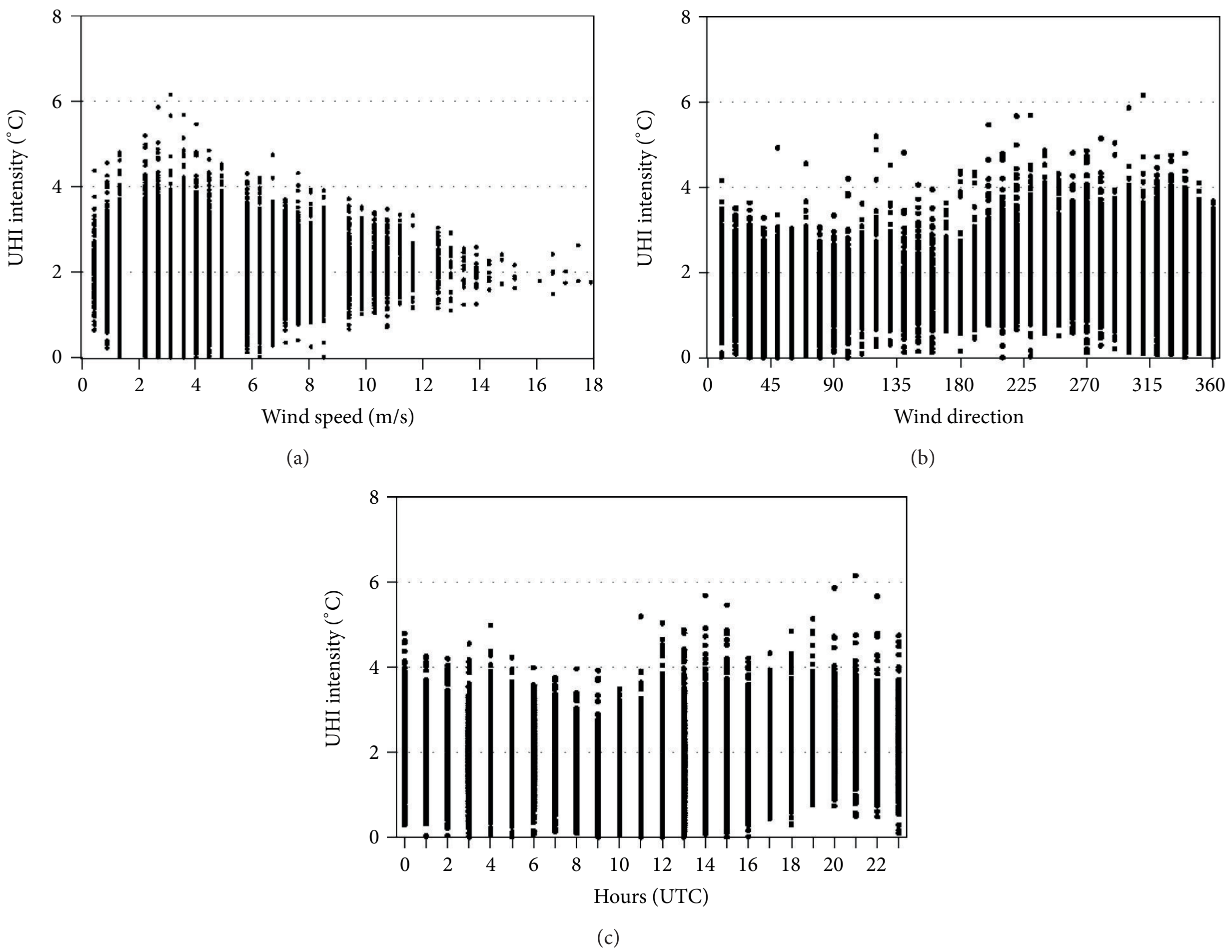

FIGURE 10: UHII versus wind speed (a), wind direction (b), and time (hours) (c).

north, northwestern, and southwestern winds. Finally, winds blowing above 8 m/s in the Airport area, seem to inhibit the occurrence of strong UHI inside the city.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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